WAVE

by Ideanomics

Wireless Extreme Fast Charging for Electric Vehicles (WXFC – Trucks)

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Project ID : elt240

June 21st - 23rd , 2022

WXFC - Trucks
Project Overview

Timeline

Project Start Date : August – 2018
Project End Date : July – 2023
Project Complete : 72 %

Barriers

- Meeting the window of time to deliver a medium voltage feed to the charge site.
- Obtaining necessary permits for the project.
- Acclimating drivers to electric vehicles requires changing driver habits (or other personnel) for plugging in the vehicles and aligning the trucks over the wireless chargers.

Budget

Total Project Funding : $ 9, 838, 240
DOE Share : $ 4, 292, 137
Contractor Share : $ 5, 546, 103
Funding for FY 2019 : $ 1, 249, 762
Funding for FY 2020 : $ 3, 603, 179
Funding for FY 2021 : $ 2, 158, 560
Funding for FY 2022 : In-progress

Partners

- WAVE, Inc – Project Lead
- Cummins, Inc (Cummins)
- Utah State University (USU)
- Schneider Electric (Schneider)
- Total Transportation Services Inc (TTSI)
- Port of Los Angeles (POLA)
- Los Angeles Department of Water & Pump (LADWP)

WXFC - Trucks

Relevance

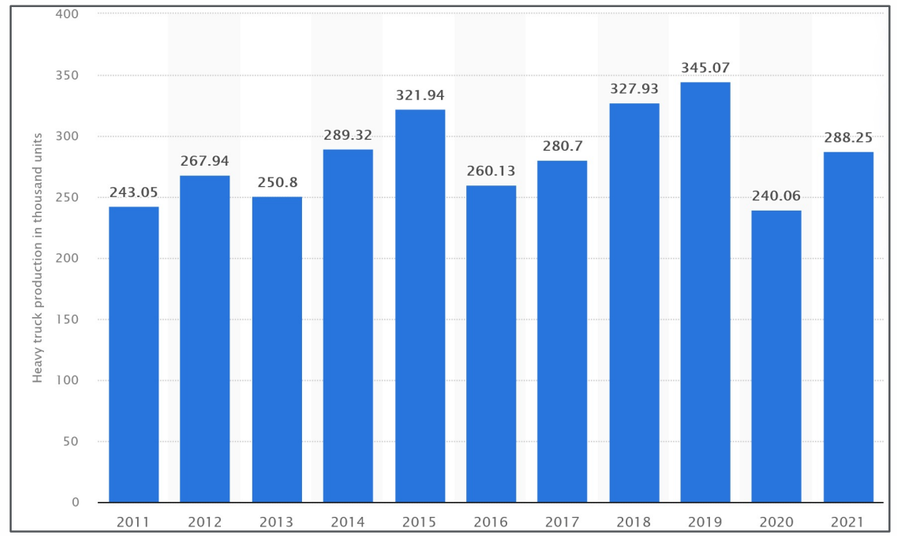
Impact

- The California Air Resource Board shows that 41% of all greenhouse gas emissions (429.5 MMTCO$_2$e in California in 2016) is due to transportation.
- 7.8% of all greenhouse gas emissions were from heavy duty trucks.
- Enabler for this major pollution transportation sector to become all-electric.
    - Fully charged vehicles in roughly 20-minutes means minimal down time to refuel and minimal impact on existing route planning.
    - No cables means hands free instant start of charging with no special personnel required.
- Overcoming the charging time obstacle leads to a 3x to 4x reduction in actual fuel costs for vehicle operation.
- Accelerate manufacturing and deployment of electric heavy-duty trucks.

Objectives

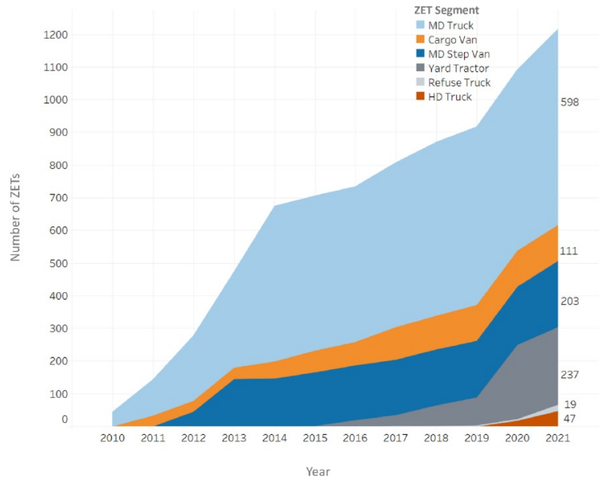
- Wireless extreme fast charging
- MV grid to DC converter
- Extreme fast charging capable electric truck

Heavy Duty Truck Production in USA 2011-2021



Zero-Emission Truck Production in USA 2011-2021

Figure 4: Cumulative Truck Deployments in the United States (2010-2021)



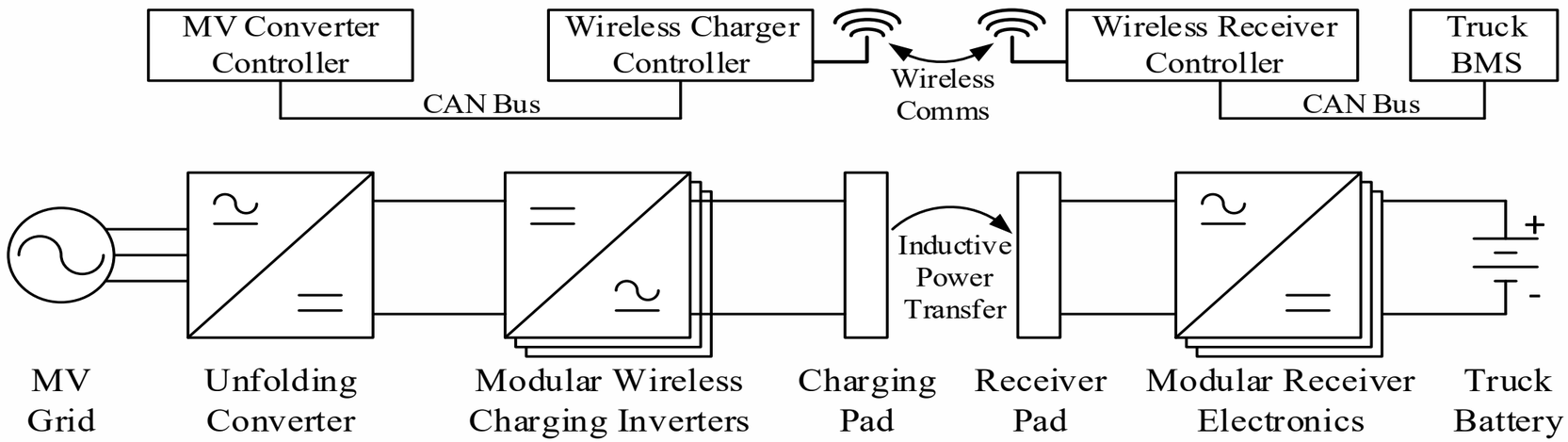
WXFC - Trucks
Relevance

FOA Objective	WXFC - Truck Expected Outcomes
Recharge battery in half the time	• New system with 500 kW wireless charging
Develop and verify vehicles equipped with XFC, charger installation demonstration	• W-XFC system deployment and operation at POLA with two Clasee-8 trucks customized to support XFC. • Deployment in two stages. First early 500 kW prototype charging and second final deployment at 500 kW. • Combined, over two years of evaluation data and best practices.
System design and grid infrastructure impact	• Direct MV 3-phase AC to DC single stage conversion solution to reduce grid integration costs, system size and weight, and improve efficiency.
Catalyze manufacturing and adoption of electric trucks	• Project goal targets key barrier to market adoption. • Over two years of system hardware demonstration and evaluation are performed at one of the world's highest volume shipping ports at a critical time with zero emission requirements in place by 2035.

WXFC - Trucks
Milestones

Budget Period 1 August 2018 - June 2020	Budget Period 2 July 2020 - July 2022	Budget Period 3 Aug 2022 - July 2023	Status
Task 0 : Project Management and Planning			
Task 1 : 500 kW Prototype Development		• Tests indicate 500kW system construction feasibility	100%
Task 2 : W-XFC 500 kW System Design and Development		• Demonstration of 500kW wireless charging with truck	100 %
Task 3: Fast Charging Electric Truck Design and Construction			89%
Task 4 : Design and construct MV Grid connected converter			22%
Task 5 : 500 kW System Integration and Testing			100%
Task 6 : 500 kW System Deployment			20%

WXFC - Trucks
Approach



Block diagram of the WXFC system from MV grid to truck battery.

WXFC - Trucks
Approach

500kW MV Grid Connected AC/DC Supply Approach

- 3-phase unfolder with a soft DC bus two-level output.
- Develop the 3-phase unfolder to achieve direct MV grid connection with switches commutating at the line frequency.
- Design the series stacked isolated DC/DC converters to achieve the voltage step down function from MV naturally with near unity conversion ration to obtain high frequency.

Extreme Fast Charging Capable Electric Truck Approach

- Investigate appropriate battery chemistry (LTO cells or NMC cells)
- Design custom thermal management for the cell to facilitate charging at 3C.
- Select appropriate battery pack capacity and cell chemistry to integrate with electric powertrain applicable to Class 8 drayage applications.

WXFC - Trucks
Approach

500kW Wireless Charging System Approach

- Leverage deployment experience with 250 kW charger.
- Use deployment experience to develop 500 kW prototype.
- WAVE has experience integrating with different OEMs.

WAVE WIRELESS BENEFITS

(JAN. 2019 – MARCH 2022)

Range extension miles delivered: **2,126,302**

Power delivered: **3,827 MWh**

Diesel fuel saved: **545,205 gallons****

Pounds of CO_2 saved: **12,954,068****

Pounds of $PM_{2.5}$ saved: **30,831****

* standard operating range of a BYD K9

** benefits attributed to using wireless charging

WIRELESS-ENABLED FLEET

Total service area: 100 square miles

Wireless charging stations: 12 @ 250kW with three more in 2021

Vehicles: 47 BYD wireless-equipped battery-electric buses

RANGE EXTENSION

Longest route covered: 600 miles (vs. operating range of 155 miles*)

State-of-charge (select routes): Buses end shift with higher SOC than start

Range extension: Double standard operating range in an 8-hour shift*/ Adds over 400 miles during 16 hours of operation

WAREHOUSE & DISTRIBUTION

SEAPORTS

TRANSIT

WXFC - Trucks
Technical Accomplishments & Progress

Completed the HF transformers fabrication and the initial UL review

External Hardware Coordination

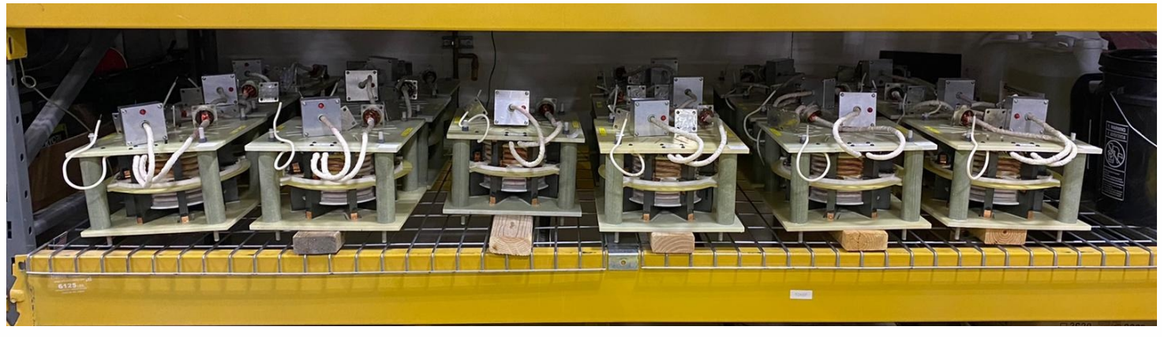
- Coordinated with Schneider Electric to design and receive the AC-DC cabinet
- Coordinated with Schneider Electric to finalize the Motorpact design
- Finalized the initial desk review with UL for the 560-kW design

Internal Hardware Development

- Procured all components needed to construct the 560-kW system
- Constructed all the enclosures needed for the MV Unfolder and all DC-DC modules
- Received and tested all the transformers from the vendor for quality and UL compliance
- Designed and fabricated all circuit boards required for control, communication, sensing, and protections

Unfolder and DC-DC Enclosures

AC-DC Cabinet Received from SE



Fabricated HF Transformers

WXFC - Trucks
Technical Accomplishments & Progress

560kW MV Grid Connected AC/DC Supply Progress

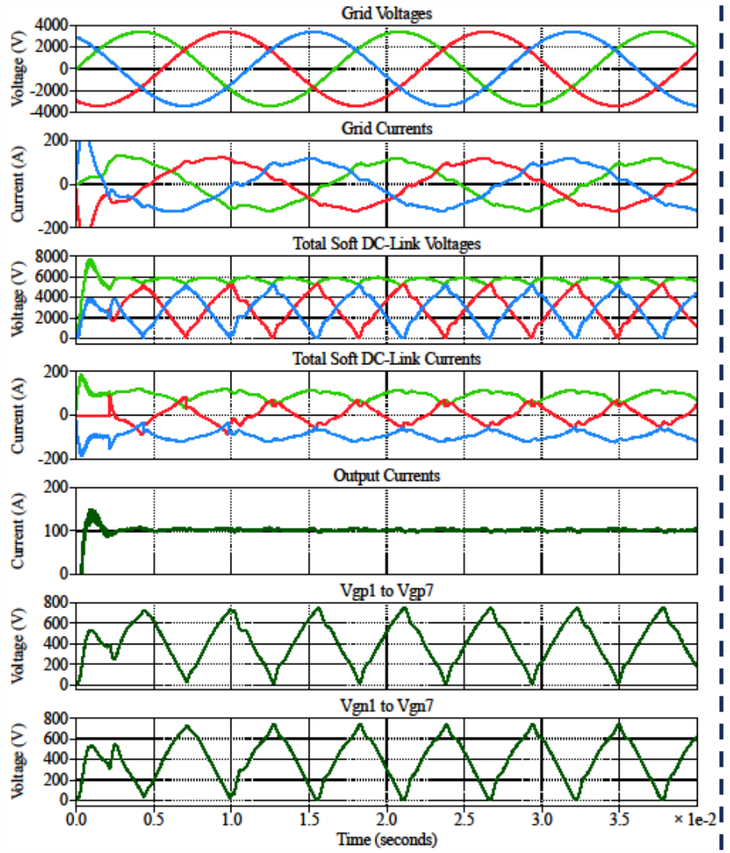
Completed the full 560 kW system simulations and demonstrated the three-port series stacking control

External Software & Control Coordination

- Determined the SE contactor control requirements and incorporated the design into the AC-DC system
- Coordinated with WAVE to evaluate the WPT system dynamics and finalize the control requirements
- Coordinated with WAVE on establishing a communication basis between the USU and the WAVE systems

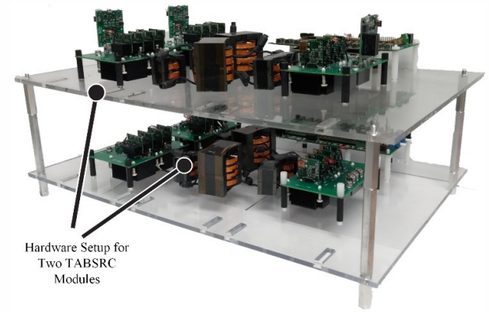
Internal Software & Control Development

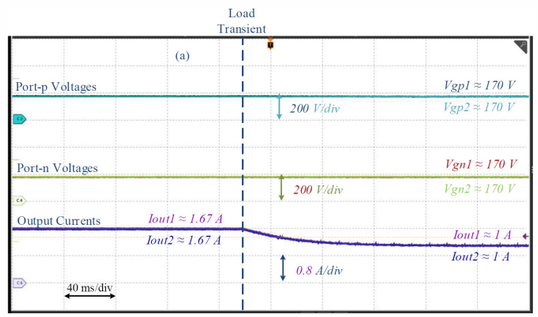
- Demonstrated the three-port series stacking control in hardware.
- Completed the full 560 kW simulations, demonstrating the functionality of the implemented (SE + USU + WAVE) hardware.

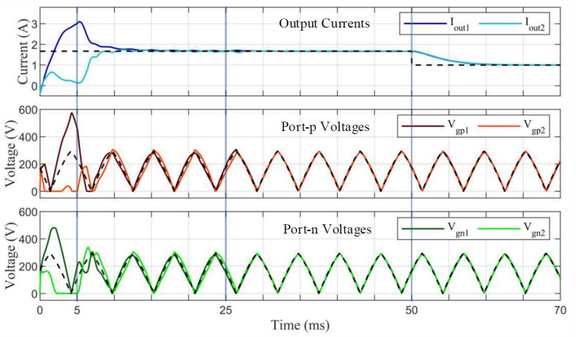


560 kW Simulations

2 kW Simulations and Hardware Results







WXFC - Trucks
Technical Accomplishments & Progress

- WAVE Equipment Builds - **Complete**
  - Primary Cabinet (2x)
  - Primary Pads (2x)
  - Secondary Pads (4 – 2x/truck)
  - Rectifier (2 - 1x/truck)

- Cummin's Trucks - **Complete**
  - 3C Charging Capable Battery Pack
  - Truck 1 & 2 Construction Complete
  - Truck 1 Delivered to WAVE

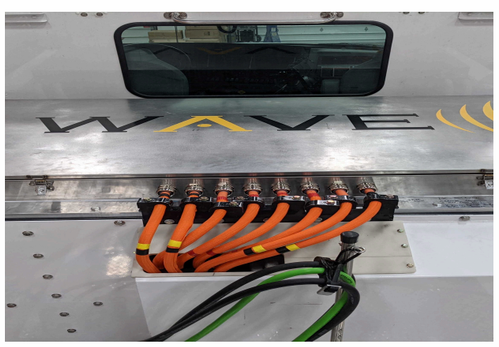
- WAVE systems Integration w/ Cummins Truck 1- **Complete**
  - Secondary Pads
  - Rectifier, Antenna & LV Control Box

- Wireless Charging w/ Vehicle - **Complete**
  - Communications Testing
  - Contactor Operations / Shutdown Function
  - Charging of Individual Pad Sets – 250 kW
  - **Dual Pad Charging – 500 kW**
  - **3C Charging of Reconfigured Battery Pack**

Cummins Truck @ WAVE

Charge Testing Set up

Secondary pads



Rectifier Unit

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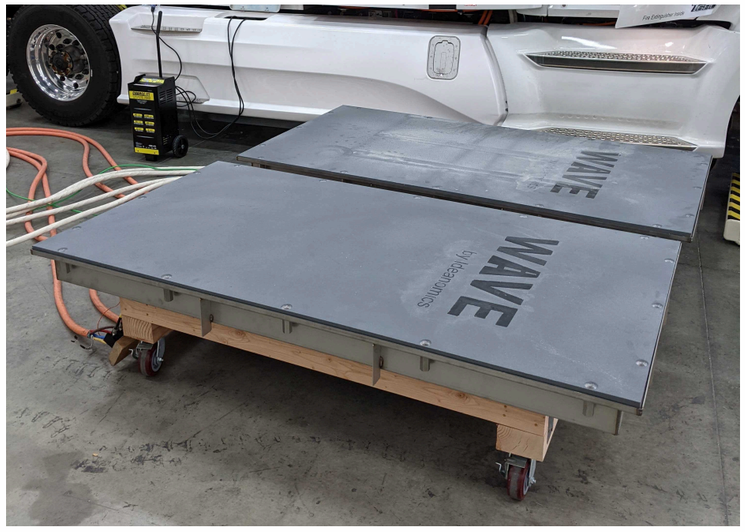
Technical Accomplishments & Progress

- **Primary Pads**
  - Cost : Same as production 250 kW pad
  - Dimensions :
    - WXFC Primary Pad : ~ 50% smaller



Primary Pads

- **Secondary Pads**
  - Cost : Same as production 250 kW pad
  - Dimensions :
    - WXFC Secondary Pad : ~ 50% smaller
  - Weight :
    - Total Weight Savings : ~ 500 lbs

Secondary Pads

WXFC - Trucks
Technical Accomplishments & Progress

	2020-21	2021-22
500 kW System	• Production design work completed and on order.	• Production charging pads, Primary inverter cabinets, Rectifiers, Cooler and other systems are built and integrated to Truck 1.
Compact Design	• Final design to have 25% weight reduction from original prototype.	• Final design is 500 lbs lighter than the current production pad. • Both Primary and Secondary pads are 50 % smaller than current production pads.
Validation Testing	• Initial testing was performed between the pads in a lab setting.	• Charge testing was done with the production pads installed to Cummins Truck 1. • Transferred ~ 500 kW between the pads. • Demonstrated 3C charging with the battery pack on the truck. • Max cell temperature reached was 29 °C.

WXFC - Trucks
Technical Accomplishments & Progress

Truck requirements

- Class 8-day cab based on TTSI's requirements.
- Battery selected which supports 3C charging, 2C discharging.

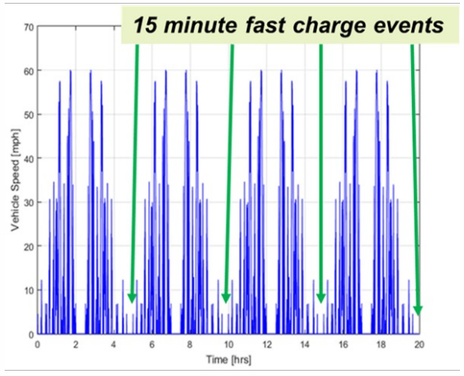
Electric Powertrain

- Cummins-developed 330 kW (continuous) central drive

Truck status

- Trucks undergoing validation in Columbus, Indiana (test track and public roads)
- Wireless charging (495 kW) demonstrated at WAVE in Q3 2021

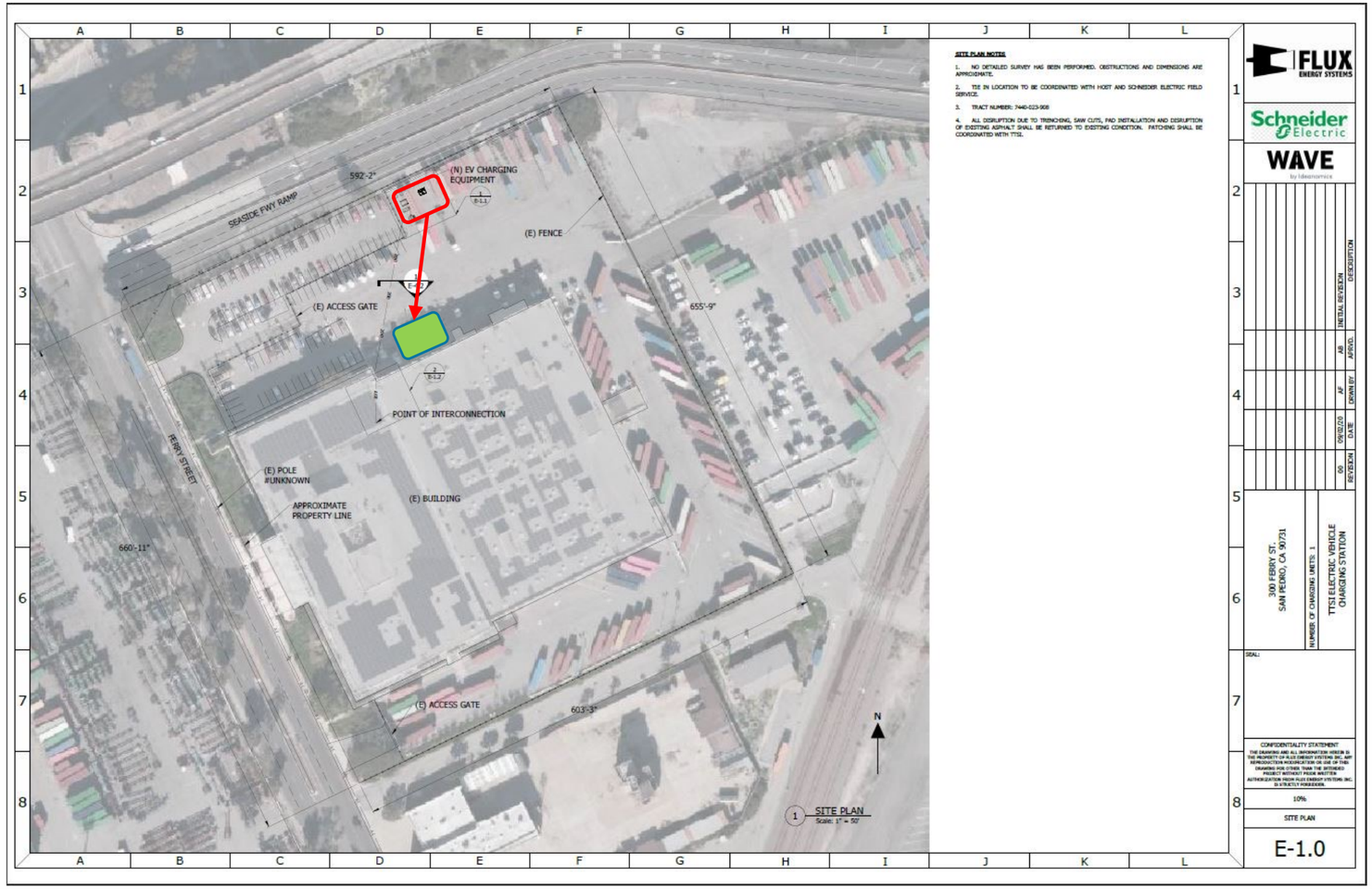
Key vehicle metrics	Target	As designed
Vehicle speed on 6% grade @ 82k lb GCVW	> 30 mph	32 mph
Charge power to 80% SOC (15 minutes)	495 kW	495 kW
Tractor weight	≤ 22.5k lb	22.8k lb
Vehicle range	45 miles	58 miles
Work-day duty cycle	20 hours 160+ miles	20 hours 200+ miles



WXFC - Trucks
Technical Accomplishments & Progress

Site Plan :

- Charger location is now relocated closer to the breaker location.
- Revision of electrical and civil drawings are in progress.
- APP (Application for Port Permits) and Project approval application requests are submitted to POLA. Pending approval.
- Breaker orders submitted to Schneider Electric.



WXFC - Trucks

Response to Previous Year's Reviewers' Comments

Approach

Reviewer: "*more details on the feasibility versus the project goals, specifically on a breakdown of anticipated hardware costs versus targets for both charging pad and the vehicle-based hardware.*"
Response: WAVE was able to accomplish 50 % smaller pad size and around 500 lbs weight reduction with the same cost to a make a current 250 kW pad.

Technical Accomplishments & Progress

Reviewer: *"It does appear the team is behind, and it is unclear how much system validation can be accomplished relative to what may have been planned at the beginning of the project"*
Response: WAVE and Cummins have completed the integration and charge testing as planned and met the milestone targets of 500 kW power transfer and 3C charging.

Collaboration & Coordination Across Project Team

Reviewer: "The reviewer stated that the integration of the design progress reflects significant collaboration and coordination by the various partners."
Response: Timely communication and quick responses between the teams have helped resolve issues faster and mitigate delays in the project.

Proposed Future Research

Reviewer: "It is not clear where the project team is relative to the 92% efficiency goal."
Response: In the initial charge testing, WAVE has achieved > 92% efficiency from grid to battery with 480 V feed. Plan to complete the final charge testing this summer and present the results.

Relevance

Reviewer: "The ability to minimize "fueling times" is critical to making BEVs of this size feasible to that particular population of vehicles."
Response: The current project addresses this issue; WAVE was able to significantly reduce the charge time by transferring energy at 3C rate.

Resources

Reviewer: "The reviewer stated that the main resource that appears to be strained is the schedule timeline due to unanticipated delays in establishing the MV grid power supply"
Response: Supply chain is still a big concern; WAVE has taken steps predicting further delays to MV equipment and ordered power supplies in advance.

WXFC - Trucks
Collaborations & Coordination

WAVE by Ideanomics — Wireless XFC System

Cummins — Truck integration and Electric Drivetrain Partner

Utah State University — MV Grid Connected AC-DC Supply, Research partner

TTSI — Port Trucks Partner

Schneider Electric — Electrical Supplier and Industrialization Partner

LA The Port of Los Angeles — Deployment partner

LA DWP Los Angeles Department of Water & Power — Electric Utility

WXFC - Trucks
Remaining Challenges & Barriers

MV-Grid Converter :

- MV cabinets delayed due to supply chain issues; MV grid converter validation to be performed at USU separately.
- Replace MV power supply with resonant power supply units.

Site Deployment & Project Demonstration :

- Final project approvals pending from POLA.
- Breaker inspection and procurement of breakers in time before deployment.
- Demonstration at site will be performed with a 480V feed instead of 4160V feed.

WAVE System :

- Automation of charging system to deliver 500 kW power.
- Truck integration and final charge testing with Truck -2.

Truck Design :

- 6-phase inverter validation and thermal management of the battery system.

WXFC - Trucks
Proposed Future Research

Future Research Opportunities :

- Battery : To improve long-term commercial viability, industry needs to develop a low-cost, higher energy density 3C charge (continuous) capable battery.
- Grid Feed : Optimize MV-to-DC converter for various electric utility MV voltages available.
- Thermal : Minimization of heat generated and novel thermal materials.
- Operator Cost : Addition of stationary storage to offset demand and TOU charges.
- System : Overall improved system-level efficiency

Any proposed future work is subject to change based on funding levels.

WXFC - Trucks
Summary

This project brings together all three critical components needed to solve the barrier for adoption of electric heavy-duty vehicles :

- High-efficiency MV Grid to lower energy costs and reduce total footprint of equipment.
- High-efficiency, high energy density wireless extreme fast charger.
- An all-electric vehicle capable of high c-rate charging and equipped to handle a wireless charging system.

The project's overall system approach is driving research that will result in a highly cost-effective solution that will make adoption of all-electric fleets not only visible, but very compelling.

Critical success factors include :

- Development of a 500kW wireless charging system.
- Development of a Class-8 truck powertrain with a battery pack capable of reliably and repeatedly charge at a greater than 3C rate up to 500 kW.
- Development of a modular direct MV 3-phase AC to DC power converter.
- Achieve MV grid system to vehicle battery efficiency of 92%.